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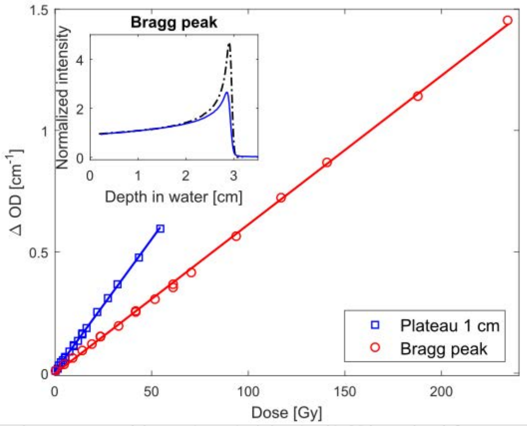
Purpose or Objective: In proton therapy, anatomical changes may cause considerable deterioration of the delivered dose distributions. Transmission-based treatment verification is generally not possible, making three-dimensional (3D) dosimetry a promising tool for verification of the delivered dose. However, solid state 3D detectors have significant problems related to linear-energy-transfer dependent quenching in particle beams – an under-response of the signal in the Bragg peak. A new deformable, silicone-based, radiochromic 3D dosimeter has recently been developed by our group. The aim of this study was to perform the first proton beam experiments with this detector. Special attention was given to the quenching and dose-rate dependencies in general, relating these effects to the chemical composition of the dosimeter.

Material and Methods: Dosimeters (1 x 1 x 4.5 cm^3) of varying chemical compositions were produced. They contained leuco-malachite green (LMG) dye as the active component, chloroform and silicone elastomer.
Twelve different batches were irradiated with 60 MeV proton beams, using a 40 mm circular collimator, to different doses (0 – 30 Gy). Irradiations were performed with both a low and a high dose rate (0.23 and 0.55 Gy/s). For comparison, depth-dose distributions were measured in water with a Markus-type plane-parallel ionizing chamber. Simultaneously, dosimeters from the same batches were irradiated with 6 MV photon beams in a 10 cm square field on a linear accelerator. All dosimeters were read out before irradiation and four hours after, at a wavelength of 635 nm. The read-out was performed with a home-built 1D-scanner with a depth resolution of 0.2 mm for the proton irradiated dosimeters, while a spectrophotometer was used for the photon read-out. The dose-rate dependency was compared for proton and photon irradiations. The ratio of Bragg-peak to plateau response (at 1 cm) was compared between batches.

Results: The effect of lowering the dose rate was similar for proton and photon beams, although the beam qualities were different. The dose response was higher at a low dose rate, but at increasing dye concentration the effect was reduced.
Significant under-response was observed in the Bragg peak. The peak-to-plateau ratio was improved from (2.5 ± 0.1) to (3.0 ± 0.04) by increasing the dye concentration from 0.1 to 0.3 % (w/w). By increasing the curing-agent concentration from 5 to 9 % (w/w), the ratio further improved to (3.7 ± 0.4) and (3.5 ± 0.1) for the same respective dye concentrations.



The dose response (change in optical density (Δ OD) vs. dose) for protons has been plotted for the plateau at 1 cm depth (blue squares) and for the Bragg peak (red circles). The lower sensitivity in the Bragg peak is clearly observed. The dose response is linear in both cases; 0.011 cm-1 Gy-1 at the plateau and 0.006 cm-1 Gy-1 at the Bragg peak. The inset shows one example of a measured proton depth–dose profile (blue full line), which has been normalized to the ion chamber measurement (black dashed line) at a depth of 13.1 mm. The example given here is from a batch irradiated with protons at 0.23 Gy/s, where the dosimeters contained 0.23 % (w/w) dye, 1.5 % (w/w) chloroform and 5.0 % (w/w) curing agent.

Conclusion: The 3D radiochromic silicone based dosimeter has for the first time been investigated in proton beams, and it was demonstrated that chemical modifications could influence the dosimeter response.

PO-0795
Dose verification of fast and continuous scanning in proton therapy

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Purpose or Objective: Out of all techniques proposed to mitigate intra-fractional motion in particle therapy, rescanning appears to be the easiest to realize: One simply needs to apply the same field multiple times with proportionally reduced dose to average out interplay patterns (Phillips *et al.* 1992). However, dead times (e.g. energy changes, spot transitions) accumulate which lengthens the overall treatment time. Thus, efficient rescanning – possibly combined with gating and/or breath-hold – requires fast energy changes (~ 100 ms) and fast lateral scanning. The former is already established at Gantry 2 (Safai *et al.* 2012). For the latter, we pursue implementing a faster delivery technique called line scanning, in which we scan the beam continuously along a straight line while quickly modulating the speed and/or current (Schätti *et al.* 2014). In this presentation, we would like to report on the dose verification concept of line scanning.

Material and Methods: With beam current changes in less than 1 ms (Schippers *et al.* 2010) and lateral scanning speeds of up to 2 cm/ms (Pedroni *et al.* 2004), the frequency of speed and current modulation along a line can be exceptionally high. This calls for a verification system that can intervene (almost) in real-time to fulfill current safety standards. Thus, we decided to monitor the beam current and position continuously during the delivery of a single element, since errors in those two parameters directly impair the homogeneity of the delivered dose distribution. In addition to these real-time verification measures, we implemented a final, redundant verification step, in which the overall dose profile of the delivered line is validated.

Results: We investigated time-resolved signals from (a) two planar ionization chambers in the gantry nozzle to monitor the beam current and (b) two Hall probes in the sweeper magnets to verify the lateral beam position. Tolerance bands define acceptable fluctuations of all signals. We implemented the readout in detector-specific firmware, running at a sampling rate of 100 kHz. This allows us to initiate interlocks in a few ms whenever limits are exceeded. Figure 1 shows the Hall probe signal during the application of a corrupt line. We simulated two position errors of ± 1 mm at iso-center during its application; both clearly visible (peak downwards, peak upwards). In the redundant verification step, we compared the dose profile of each line, measured with a strip chamber in the nozzle, to a forward-calculated expectation.

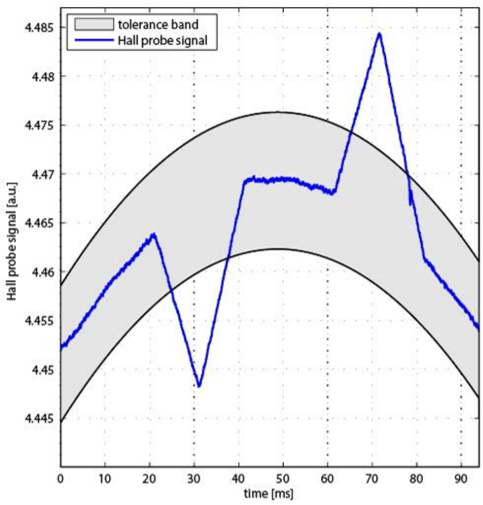

Figure 1: Measured Hall probe signal during the application of a corrupt line. Both delivery errors in position (± 1 mm at iso-center) push the signal outside of the pre-defined tolerance band (here at t_1 = 25 ms and t_2 = 65 ms). Short reaction times in initiating interlocks prevent clinically unacceptable distortions of the delivered dose distribution. The curved signal shape originates from a non-linear correlation between the magnetic field of the sweeper and the actual beam position.

Conclusion: Line scanning is a fast scanning technique; well-suited to rescanning, because it can deliver entire low-dose fields within a few seconds. The combination of real-time verification and dose profile validation ensures safe beam delivery. Interlocks can be initiated quickly during the application of a line if continuously monitored signals exceed pre-defined tolerance limits.

PO-0796

Dose rate dependence of the PTW 60019 microDiamond detector in high dose-per-pulse pulsed beams

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Purpose or Objective: Recombination can affect detectors used for the dosimetry of radiotherapy fields, and should be corrected for. The introduction of FFF accelerators increases the typical dose-per-pulse (DPP) used in radiotherapy, which leads to more important recombination effects.
Diamond detectors provide a good solution for the dosimetry of small fields, due to their low energy dependence and small volume. The group of Università di Roma Tor Vergata has developed a synthetic diamond detector, commercialized by PTW as microDiamond. In this work we present an experimental characterization of the collection efficiency of the this detector, focusing on high-DPP, FFF beams.

Material and Methods: Measurements were performed in a Truebeam linac (Varian) with FF and FFF modalities. The microDiamond chamber was placed in a cubic PMMA phantom at 10 cm depth, the detector axis perpendicular to the beam axis. The source-to-detector distance was varied between 70 cm and 150 cm to change the DPP. The detector was irradiated with different modalities (6MV-FFF, 10MV-FFF, and 10 MV for reference) and monitor unit rates. The detector was pre-irradiated with ~15 Gy, enough to achieve signal stability. Leakage current was measured before and after each irradiation, and was always found to be <0.1 pA. We also performed measurements with a CC13 air ionization chamber (IBA, Belgium) for reference. Collection efficiencies for the microDiamond detector can qualitatively be obtained from ratios of detector readings.

Results: The collection efficiency decreases with DPP, down to 0.978 at 2.2 mGy/pulse. The effect is within 1.1% in the range 0.1-2.2 mGy/pulse, referred to 0.5 mGy/pulse. This dependence is similar to the value reported in the user manual in a narrower dose-per-pulse range (0.05-0.8 mGy).
The collection efficiency versus DPP curve does not show the typical linear dependence observed in the near saturation region for ionization chambers, but an equation based on the Fowler-Attix model provides a good fit. Such different behaviour is not surprising: recombination in diamond detectors is a more complex physical process than it is in ionization chambers, with impurities playing a significant role.
On the other hand, we have found no significant dependence of the collection efficiency on pulse repetition frequency.

Conclusion: The dose rate dependence of the microDiamond is within 1.1% in the range 0.1-2.2 mGy/pulse referred to 0.5 mGy/pulse The dependence, though moderate, can cause some systematic discrepancies when measuring FFF beams with different DPP values and should probably be considered.

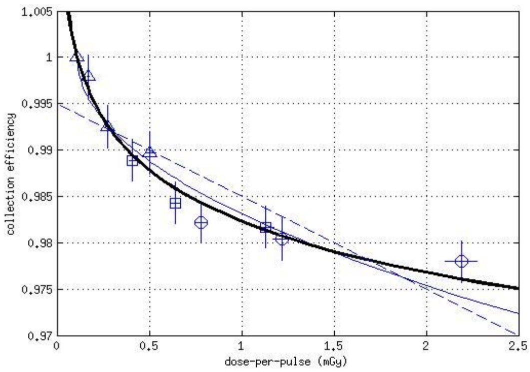

Figure. MicroDiamond collection efficiencies versus DPP: 10 MV (triangles), 6MV-FFF (boxes) and 10MV-FFF beams (circles). Best fits to a linear dependence on the dose-per-pulse (dashed line), an equation with a square root dependence (thin solid line), and the Fowler-Attix expression (thick solid line), are showed.

PO-0797

Advanced Radiation Dosimetry System (ARDOS) - A novel breathing phantom for radiation therapy

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Purpose or Objective: Nowadays an increasing number of techniques that account and compensate for 4D tumor motion are proposed, investigated and implemented into